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SOME ASPECTS OF THE COMPATIBILITY BETWEEN STRAIN GUAGE
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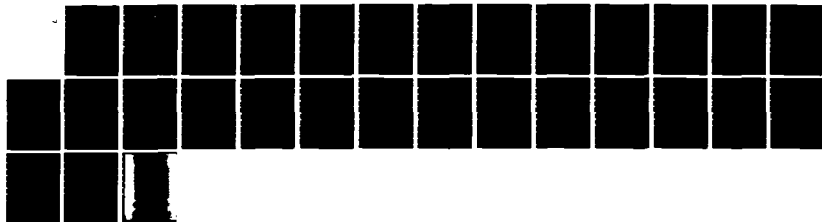
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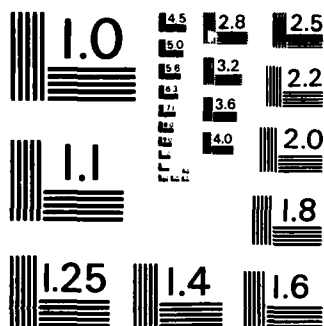
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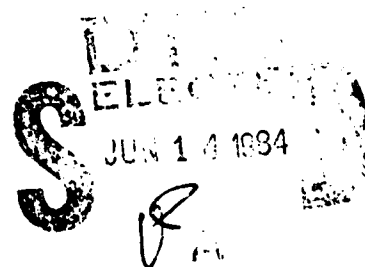
**SOME ASPECTS OF THE COMPATIBILITY BETWEEN
STRAIN GAUGE READOUT EQUIPMENT AND MULTI-
COMPONENT WIND TUNNEL BALANCES**

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N. POLLOCK

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**SOME ASPECTS OF THE COMPATIBILITY BETWEEN
STRAIN GAUGE READOUT EQUIPMENT AND MULTI-
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SUMMARY

In multi-component strain gauge wind tunnel balances it is common practice to use four arm bridges of gauges arranged to produce an output from one load component and not from other load components which also cause significant strains under the gauges. This system relies on the fact that there is fundamentally one output-producing pattern of strains and three non-output-producing patterns. It is shown that interactions arise between the various strain patterns and that these interactions, and hence the balance calibration equations, are dependent on the nature of the readout equipment used. Specific precautions which must be observed to obtain 0.01% accuracy levels are investigated.



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A handwritten form with a grid structure. The grid has several rows and columns. The text 'A-1' is written in the bottom left corner of the grid. There are some faint, illegible markings in the top right corner of the grid. The form is tilted and has a textured, grainy appearance.

NOTATION

R	Resistance
V	Output Voltage
ϵ	Strain

1. INTRODUCTION

In high speed wind tunnels it is common practice to measure the aerodynamic loads acting on aircraft models with force balances located inside the model. These force balances transfer the total aerodynamic load, and the model weight, to a supporting sting which usually protrudes from the rear of the fuselage and attaches to the model attitude control system. The vast majority of these internal balances use resistance strain gauges bonded onto fabricated or machined-from-solid metal structures.¹⁻⁴ In recent years internal strain gauge balances have also been widely used in low-speed tunnel tests of jet aircraft which lend themselves to sting mounting.

It is usual to arrange for a wind tunnel balance to measure six force and moment components so the aerodynamic load acting is completely defined. In principle any six independent outputs from a balance can be used to determine the total load acting. However, unless these six outputs are well conditioned, the accuracy of determination of the total load could be poor. From an aerodynamic viewpoint it is usual practice to describe the total loading in terms of three orthogonal forces acting through the model centre of gravity and three orthogonal moments. Since this type of force and moment component system is easy to visualise and does form a well conditioned set for the determination of total load system acting, it has been usual to design balances with a similar set of outputs. It should be noted, however, that for some balance arrangements there are good reasons for departing from this system of outputs.⁵

To maintain the high accuracy required, it is usual to use separate four-active-arm bridges, where each arm may contain one or more gauges, for each of the balance outputs. Due to the space constraints imposed on balances internal to models it is not usually possible to mechanically separate the load components completely, as is done with mechanical balances which are mounted outside the tunnel test section.^{2,6} For internal balances it is usual to resort to "strain arithmetic" to separate the load components. Each bridge is arranged so that the relevant load component generates a pattern of strains under the gauges which produces an output from the bridge. Some of the other load components also produce significant strains under the gauges but the pattern of strains is such that, at least to the first order, no output is generated from the bridge. To the best of the author's knowledge wind tunnel balances represent the only large scale deliberate application of this strain arithmetic concept.

Since, for the strain levels typical of balance designs, the full scale output from each bridge is only a few millivolts, considerable amplification is required to obtain a voltage suitable for most data systems. A wide variety^{1,2,4,7} of strain gauge readout electronics are used in different wind tunnels. Some use special purpose equipment designed and manufactured in-house, some use commercial strain amplifiers intended primarily for stress analysis and others use high quality general purpose D-C amplifiers. Independent of their origins these devices are either amplifiers which amplify the bridge output voltage, and incidentally load the bridge with their input impedance, or nulling devices which inject a measured current into the bridge to maintain zero output voltage. Both types exist with either D-C or A-C bridge excitation. Most readout systems incorporate an offset adjustment to null initial gauge resistance differences and to maintain full scale resolution in the presence of large tare offsets (model weight). These offset adjusting systems have long been recognised as a potential source of problems.⁸

The vast majority of the work on strain gauge force measuring systems (balance plus readout electronics) reported up to now has considered the load cell case where significant strain arithmetic is not used, i.e. the dominant strain field under the gauges of the bridge is the one which produces the desired output. In this note the special requirements and problems of readout electronics for use with wind tunnel balances are examined. This critical examination has become particularly important with recent advances⁷ in readout electronics improving the resolution of strain gauge measurements from 0.1 % to 0.01 %.

The work reported here grew out of a specific investigation into the possibility of calibrating a balance with one type of readout equipment then using it with another type. Previous work suggests that provided the sensitivity ratios between the various channels of the two sets of equipment were known the calibration should be transferable. However the present work demonstrates that the nature of the calibration changes with the readout equipment and balances should always be calibrated with exactly the same type of equipment with which they will be used.

2. BALANCE DESIGN

Current practice in multi-component strain gauge balance design is well described in Refs 1 to 4. In recent years improved materials, fabrication techniques and stress analysis methods have been developed but the basic arrangements used have not changed significantly in over 20 years. In many of the popular designs some strain arithmetic is used to assist with the separation of the load components. This concept of strain arithmetic is well illustrated by the four beam axial force cage (Fig. 1) which is used in many balances. In this design the model loads are transferred to the earthed support through a rectangular array of four beams which are built in at both ends. These beams are deflected into an "S" shape under the action of an axial force. Since there are four beams each with two sides and two ends it can be seen that there are many arrangements of four strain gauges wired as a bridge which will produce an output for an applied axial force. However, it is well known⁹ that there is only one fundamental gauge arrangement, which exists in four different configurations, which does not also produce outputs due to other load components and differential thermal expansions of the two members on which the beams terminate.

This preferred gauge arrangement is shown in Fig. 1. For ease of exposition an axes system with its origin at the centre of the cage will be assumed. It can be seen that an X load produces a pattern of strains under the gauges which unbalances the bridge and therefore produces an output. When the upper and lower beam attachment members are at different temperatures, as they often are since one connects to the model and the other to the support system, the different expansion of the two members will produce strains in the beams which produce a strain pattern under the gauges which does not unbalance the bridge and therefore produces no output. Likewise it can be seen that the strain patterns produced by Z , l and m loads also produce an output. If the gauges are exactly on the centrelines of the beams the Y and n loads do not produce strains under the gauges.

It has been argued⁵ that the deliberate use of strain arithmetic should be avoided since it involves a loss of precision where different calibration equations are used for positive and negative loads in each component. However for cases like the four beam X cage discussed above the practice will undoubtedly continue since the alternative is to place a strain gauge bridge on each beam with a resulting increase in the number of balance outputs which require processing. Even if four bridges were used strain arithmetic would continue unintentionally since each bridge would be subject to common mode compressive or tensile strains under z , m and l loads. All practical strain gauge wind tunnel balances involve some unintentional strain arithmetic and most current designs use the technique deliberately.

3. BALANCE CALIBRATION

It has been found^{10,5} that to adequately describe the behaviour of most wind tunnel balances a set of n equations of the following form are required:

$$\begin{aligned} V_1 = & C_{1,1}F_1 + C_{1,2}F_2 + \dots + C_{1,n}F_n \\ & + C_{1,11}F_1^2 + C_{1,22}F_2^2 + \dots + C_{1,nn}F_n^2 \\ & + C_{1,12}F_1F_2 + \dots + C_{1,(n-1)n}F_{(n-1)}F_n \end{aligned}$$

where

n = Number of components measured ($n \leq 6$)

$i = 1$ to n

V = Output reading

F = Load component

$C_{i,i}$ = Direct sensitivity of i th component

$C_{i,j}(i \neq j)$ = Linear or first order interaction terms

$C_{i,jj}$ = Load squared terms

$C_{i,jk}$ = Load cross product terms

The $C_{i,jj}$ and $C_{i,jk}$ terms are collectively referred to as second order interaction terms. For a six component balance a total of 162 C 's must be determined during the calibration process. Sometimes⁵ the values of the coefficients in the equations are assumed to depend on the signs of the various component loads, to account for any discontinuity in the variation of output with load occurring at zero load. If this is done the total number of C 's to be determined for a six component balance increases to 504. The balance calibration is accomplished by applying enough known single loads or combinations of loads to define as many of the C 's as are necessary to achieve the required measurement accuracy.

When the balance strain levels are low it is sometimes possible to obtain acceptable accuracy using only the 36 first order and direct sensitivity terms. This not only simplifies the calibration procedure but also allows a direct determination of the applied loads from the readings rather than the iterative solution required for balances with second order interaction terms.

Since for small deflection linear superposition of stresses applies, it has generally been assumed that second order interaction terms have their origin in balance deflections. However it is demonstrated in this note that second order interaction can arise on "rigid" balances due to the behaviour of strain gauge bridges and the associated readout electronics.

4. READOUT ELECTRONICS

Most strain gauge balances in current use have output strains at the gauge locations in the range $200 \mu\text{m/m}$ to $2000 \mu\text{m/m}$. Most balances use metal resistance strain gauges with a gauge factor of about 2 and except in a few special circumstances they are wired as full four active arm bridges since this arrangement gives the highest output and minimum drift. Considerations of gauge self heating lead to the use of bridge excitations in the range 1 to 10 volts. The above values of strain, gauge factor and excitation voltage lead to maximum bridge output voltages in the range 0.4×10^{-3} to 40×10^{-3} . It is therefore necessary, particularly for the lower outputs, to use some form of amplification to produce signal levels suitable for most data acquisition systems.

A wide variety of amplifier types are used^{1,2,4,7}, but basically they fall into two categories. The first category consists of simple amplifiers and the input impedance is the only system parameter which influences the bridge behaviour (assuming the amplifier input offset and bias currents are small). In general simple amplifiers either have an input impedance much higher than the gauge resistance and therefore behave like open circuit voltage amplifiers or a very low input impedance and act like short circuit current amplifiers.

The second category of strain gauge bridge readout equipment is the current-injection-nulling type where a servo loop is used to inject a current into one corner of the bridge to maintain the bridge output at zero. The bridge output is measured by the rebalancing current. It should be noted that the simple current amplifier can be viewed as a special case of a current injection nulling system where the current injected into one corner of the bridge is extracted from the opposite corner. The two categories of bridge readout system exist in both AC and DC excited versions.

It is usual to have an adjustable resistance network directly connected to the bridge to remove zero offsets due to gauge mismatching and tare offsets caused by heavy models. If such a zero adjusting network is provided it is obviously essential that the system calibration is not changed in any way when the offset is altered. The problem of variation of direct sensitivity with offset adjustment has been discussed previously by Tiffany and Wood.⁸

5. OUTLINE OF INVESTIGATION

For a four active arm bridge there is only one pattern of strains under the gauges which produces an output. This pattern is when + and - (tensile and compressive) strains alternate around the bridge (Fig. 2) and in this note the output producing strain pattern will be referred to as the primary strain pattern. Consideration of the possible strain patterns reveals three non-output-producing or secondary types. These are defined in Fig. 2. All of the strain patterns exist in the form shown in Fig. 2 and with the strain signs interchanged. Since the two forms behave identically as far as the following analysis is concerned they are considered to be fundamentally the same and all conclusions drawn apply equally to both signs. For simplicity all strains, gauge factors and initial gauge resistances will be considered to be equal in the following analysis. This simplification is not thought to limit the generality of the conclusions reached. However it is possible that in the real case where the strain, gauge factor and initial resistance are different for each gauge in the bridge, high order effects not revealed by the present analysis would appear.

The basic approach followed is to calculate the system output when each of the secondary strain patterns is superimposed on the primary pattern. Both strains were varied in the range 0 to 0.002 m/m, the initial gauge resistance was 120 Ω and the gauge factor was 2. For initial gauge resistances other than 120 Ω all resistance values should be multiplied by the ratio gauge resistance/120. For gauge factors other than 2 all strain levels should be multiplied by the ratio 2/gauge factor. It was decided to present this work in dimensional form with typical values of gauge factor and resistance rather than in non-dimensional resistance ratio form so that the conclusions could be more readily compared with current practice.

The gauge resistances were calculated from:

$$R_i = (1 + k(\epsilon_{\text{primary}} \pm \epsilon_{\text{secondary}}))R_0 \quad (1)$$

where:

i varies from 1 to 4

k = Gauge factor = 2

ϵ = Strain

R_0 = Initial gauge resistance = 120

and the sign depend on i and the secondary strain type (Fig. 2).

When a simple standard nulling network of the type formed by R_6 and R_7 in Fig. 3 was considered, the circuit was simplified by applying a star-delta transformation to R_6 and the two parts of R_7 then combining the resulting parallel resistor pairs. The resulting resistor R_{70} shunting the whole bridge (Fig. 3) had no effect except to load the excitation supply and was therefore not included in the calculations. For a non-nulling system with an amplifier input impedance of R_5 (Fig. 3) the output voltage is directly proportional to the voltage drop across R_5 , assuming the actual amplifier to be free from errors. From Ref. 11 the voltage across R_5 is given by:

$$V_5 = \frac{E(R_1 R_{40} - R_2 R_{30})}{(R_1 + R_2)(R_{30} + R_{40}) + \frac{R_1 R_2 R_{40} + R_1 R_2 R_{30} + R_1 R_{30} R_{40} + R_2 R_{30} R_{40}}{R_5}} \quad (2)$$

The outputs of all non-nulling systems were calculated using Equations (1) and (2) and where appropriate the simplification of the offset adjusting network given in Fig. 3. The arrangement

of the most common type of nulling system is shown in Fig. 4. A servo loop is used to drive V_0 to the value required to maintain the bridge output at zero. Since there is no bridge output voltage the null sensing amplifier input impedance is immaterial. From Fig. 4:

$$V_a = E \left(\frac{R_2}{R_1 + R_2} - \frac{1}{2} \right) = V_b \quad (3)$$

$$I_3 R_3 + (I_3 + I_5) R_4 = E \quad (4)$$

$$(I_3 + I_5) R_4 = V_a + \frac{E}{2} \quad (5)$$

$$k V_0 E - V_b = I_5 R_5 \quad (6)$$

From Equations (3) to (6):

$$V_0 = \frac{1}{k} \left[\frac{R_2}{R_1 + R_2} \left(\frac{R_5}{R_4} + \frac{R_5}{R_3} + 1 \right) - \frac{1}{2} \frac{R_5}{R_3} \right] \quad (7)$$

The outputs of all nulling systems were calculated using Equations (1) and (7). Where an offset adjusting network was used it was simplified as shown in Fig. 3 before the application of Equation (7).

An accuracy of 16 significant figures was maintained for all calculations. This was rendered necessary by the form of the expressions resulting from bridge network analyses.

6. RESULTS AND DISCUSSION

6.1 Non-nulling system without zeroing network

To examine the case of a near perfect voltage amplifier as the bridge output device an amplifier input impedance of $10^9 \Omega$ was selected. For the primary strain pattern acting alone the system output varied perfectly linearly with the strain, i.e. $V \propto \epsilon_0$. When the three secondary strain types were each individually combined with the primary type the following output relationships were found:

$$\text{Type 1. } V \propto \epsilon_0 - 2\epsilon_0\epsilon_1$$

$$\text{Type 2. } V \propto \epsilon_0 + 4\epsilon_0\epsilon_1^2$$

$$\text{Type 3. } V \propto \epsilon_0$$

In these relationships, and in those presented later, only the dominant interaction terms resulting from each strain type are shown.

The type 1 behaviour is equivalent to a second order interaction between the two load components producing the ϵ_0 and ϵ_1 strains. This second order interaction would contribute 0.4% to the output when $\epsilon_0 = \epsilon_1 = 0.002$. The type 2 behaviour is equivalent to a high order interaction between load components of a type which is not normally included in balance calibration equations. Fortunately this high order term only contributes 0.0016% of the output for $\epsilon_0 = \epsilon_1 = 0.002$ and therefore can be safely ignored. The type 3 strain field has no effect on the bridge output.

To simulate a low input impedance current amplifier an input resistance of 0.01Ω was assumed and the offset nulling resistors were set at $10^9 \Omega$ as before. The system behaviour was as follows:

$$\text{Type 0 alone. } V \propto \epsilon_0 + 4\epsilon_0^3$$

$$\text{Type 1. } V \propto \epsilon_0 + 4\epsilon_0^3 - 4\epsilon_0\epsilon_1$$

$$\text{Type 2. } V \propto \epsilon_0 + 4\epsilon_0^3 + 4\epsilon_0\epsilon_1^2$$

$$\text{Type 3. } V \propto \epsilon_0 + 4\epsilon_0^3 + 4\epsilon_0\epsilon_2^2$$

The third order ϵ_0^3 , $\epsilon_0\epsilon_1^2$ and $\epsilon_0\epsilon_2^2$ terms only contribute about 0.0016% each to the system output for strain levels of 0.002 and can therefore be neglected. The second order $\epsilon_0\epsilon_1$ term is twice as large as the equivalent term for the high impedance amplifier case and now contributes 0.8% to the output for $\epsilon_0 = \epsilon_1 = 0.002$.

As the amplifier input impedance is varied between very high and low values the second order $\epsilon_0 - \epsilon_1$ interaction is the only significant quantity which changes. To investigate the implications of this interaction on amplifier selection and interchangeability the effect of varying the input impedance R_5 on the interaction was calculated. The results of these calculations are shown in Fig. 5. It can be seen that amplifiers with an input impedance above about 8 k Ω can be interchanged without altering the form of the calibration equations although the direct sensitivity may have to be adjusted to account for the different bridge loading. Similarly amplifiers with an input impedance of less than about 2 Ω can be interchanged without altering the interaction terms in the calibration. In the input resistance range 2 Ω to 8 k Ω any change in resistance will require a recalibration.

6.2 Nulling system without zeroing network

The small signal gain of the nulling system shown in Fig. 4 is plotted against rebalancing resistance in Fig. 6. For the normal range of strain levels and output voltage requirements a rebalancing resistance of the order of 100 k Ω will be needed. Calculations of the system behaviour with $R_5 = 100$ k Ω revealed the following output relationships:

- Type 0 alone. $V \propto \epsilon_0 + 4\epsilon_0^3$
- Type 1. $V \propto \epsilon_0 + 4\epsilon_0^3 - 4\epsilon_0\epsilon_1$
- Type 2. $V \propto \epsilon_0 + 4\epsilon_0^3 + 2\epsilon_0\epsilon_2$
- Type 3. $V \propto \epsilon_0 + 4\epsilon_0^3 + 0.0003 \epsilon_3$

Comparing these relationships with those presented in the previous section for non-nulling systems it can be seen that there are a number of differences. The most significant change is the appearance of a significant second order $\epsilon_0\epsilon_2$ interaction which did not occur for a non-nulling system. This term would contribute 0.4% to the output reading for $\epsilon_0 = \epsilon_2 = 0.002$. The second order $\epsilon_0\epsilon_1$ interaction is the same as for a non-nulling system with an amplifier input impedance of less than 2 Ω . The first order ϵ_3 term could be significant if a high Type 3 strain was used.

The basic conclusion to be drawn is that nulling and non-nulling readout equipment cannot be interchanged without a complete recalibration of the balance because the apparent interactions will be changed as well as the direct sensitivities.

The variation of the interaction terms with changes in the rebalancing resistance is shown in Fig. 7. It can be seen that all the interaction terms vary significantly as the resistance is reduced. In the absence of significant Type 3 strains, R_5 values down to about 2 k Ω can be used while retaining 0.01% accuracy. For R_5 values below this a separate calibration would be needed for each resistor value. Fortunately an R_5 of 2 k Ω would produce a gain much lower than would usually be required. If large Type 3 strains were used the minimum R_5 value that could be used without recalibration would be about 200 k Ω and this could pose a problem with a high output balance. Nulling systems are not well suited to high output balances since the system sensitivity can not be changed (by altering R_5) without altering a significant number of interaction terms in the balance calibration equations. For this reason nulling systems should only be used with semi conductor strain gauges at very low strain levels.

6.3 Non-nulling system with zeroing network

All practical strain gauge balance readout systems have some form of zero offset adjustment to make full use of the system output span in the presence of initial bridge unbalance and offset loads due to the model tare weight. If the offset adjustment is changed during a test to balance out different tare loads when the model configuration or attitude is changed, or if it is adjusted between calibration and test, it is essential that the system calibration is not altered

by the changed offset. The most common type of zero offset network is shown in Fig. 3. However at least one type of commercial equipment known to the author has this network rotated 90° around the bridge so that the potentiometer R_7 is across the bridge output and R_8 connects to one side of the supply.

In the following analysis a zero offset of 0.001 m/m was adopted as a standard test case since it represents a severe but practically possible condition. The value of R_8 was fixed at $10\text{ k}\Omega$ since this gave the required authority for all practical values of R_7 . The actual potentiometer movement (α) (Fig. 3) required to produce a $\epsilon = 0.001$ offset varied with R_7 . The most obvious requirement for an offset nulling network is that it should not alter the direct sensitivity of the system when adjusted. The effect of the two types of nulling network mentioned above on the sensitivity of a high input impedance ($10^9\ \Omega$) non-nulling system is shown in Fig. 8. It can be seen that the 90° rotated nulling network gives poor results and should not be used. It was found that the poor performance was primarily due to the effect of the resistance R_{70} (Fig. 3) shunting the amplifier input impedance R_5 . For the conventional network, as was shown in earlier work,⁸ the sensitivity change with offset increases as R_7 is increased (Fig. 8). To keep the sensitivity change to less than 0.01% for a $\epsilon = 0.001$ offset, R_7 should be less than $2\text{ k}\Omega$.

To investigate the effect of offset adjustment an interactions due to strain arithmetic an R_7 value of $1\text{ k}\Omega$ was adopted. For no offset ($\alpha = 0.5$) the system behaviour was as follows:

$$\begin{aligned}\text{Type 0 alone.} & \quad V \propto \epsilon_0 \\ \text{Type 1.} & \quad V \propto \epsilon_0 - 2\epsilon_0\epsilon_1 \\ \text{Type 2.} & \quad V \propto \epsilon_0 + 4\epsilon_0\epsilon_1^2 \\ \text{Type 3.} & \quad V \propto \epsilon_0 + 0.003\epsilon_3\end{aligned}$$

Comparing this with the equivalent system behaviour without a nulling network (Section 6.1) it can be seen that the two are identical except for the introduction of the first order ϵ_3 interaction term. When an offset equivalent to $\epsilon_0 = 0.001$ was introduced by setting α to 0.84 the following system behaviour emerged:

$$\begin{aligned}\text{Type 0 alone.} & \quad V \propto \epsilon_0 \\ \text{Type 1.} & \quad V \propto \epsilon_0 - 2\epsilon_0\epsilon_1 + 0.002\epsilon_1 \\ \text{Type 2.} & \quad V \propto \epsilon_0 + 4\epsilon_0\epsilon_2^2 - 0.002\epsilon_2 \\ \text{Type 3.} & \quad V \propto \epsilon_0 + 0.003\epsilon_3\end{aligned}$$

Comparing this with the zero offset behaviour shown above it can be seen that significant first order ϵ_1 and ϵ_2 interactions are introduced. It would appear that, at least for high impedance non-nulling systems with conventional zero offset controls, changes of the offset control between calibration and test or during a test should be minimised.

For a non-nulling system with a very low input impedance ($0.01\ \Omega$) preliminary calculations showed that the sensitivity was completely unaffected by zero offset for all values of R_7 . However an R_7 value of $1\text{ k}\Omega$ was adopted for consistency with the high impedance case discussed above. For zero offset ($\alpha = 0.5$) the system behaviour was found to be:

$$\begin{aligned}\text{Type 0 alone.} & \quad V \propto \epsilon_0 + 4\epsilon_0^3 \\ \text{Type 1.} & \quad V \propto \epsilon_0 + 4\epsilon_0^3 - 4\epsilon_0\epsilon_1 \\ \text{Type 2.} & \quad V \propto \epsilon_0 + 4\epsilon_0^3 - a \\ \text{Type 3.} & \quad V \propto \epsilon_0 + 4\epsilon_0^3 + 0.003\epsilon_3\end{aligned}$$

Where " a " is a complex high order interaction with a magnitude of about 0.0008% of reading for $\epsilon_0 = \epsilon_2 = 0.002$.

As for the high impedance system the major effect of the addition of the zeroing network with $\alpha = 0.5$ is the introduction of the first order ϵ_3 interaction term.

When an offset equivalent to $\epsilon_0 = 0.001$ was introduced ($\alpha = 0.84$) the system behaviour became:

- Type 0 alone. $V \propto \epsilon_0 + 4\epsilon_0^3$
- Type 1. $V \propto \epsilon_0 + 4\epsilon_0^3 - 4\epsilon_0\epsilon_1$
- Type 2. $V \propto \epsilon_0 + 4\epsilon_0^3 - a - 0.002 \epsilon_2$
- Type 3. $V \propto \epsilon_0 + 4\epsilon_0^3 + 0.003 \epsilon_3$

Comparing this with the zero offset behaviour presented above it can be seen that a significant first order ϵ_2 interaction is introduced. It is therefore apparent that for low as well as high resistance systems the offset control should be used with caution.

6.4 Nulling system with zeroing network

All the nulling systems known to the author use a zero offset network of the type shown in Fig. 3 with the resistor R_6 connected to the same corner of the bridge as the rebalancing resistor R_5 . As for the non-nulling systems discussed in the previous section, R_6 was made equal to $10 \text{ k}\Omega$ to give the desired authority. A preliminary investigation into the effect of the value of R_7 on the direct sensitivity change with zero offset produced results which were virtually identical with those for a non-nulling system with a high input impedance (Fig. 8). An R_7 value of $1 \text{ k}\Omega$ was therefore adopted to avoid significant sensitivity changes. For $R_5 = 100 \text{ k}\Omega$ which is a typical practical value and no zero offset ($\alpha = 0.5$) the system behaviour was found to be:

- Type 0 alone. $V \propto \epsilon_0 + 4\epsilon_0^3$
- Type 1. $V \propto \epsilon_0 + 4\epsilon_0^3 - 4\epsilon_0\epsilon_1$
- Type 2. $V \propto \epsilon_0 + 4\epsilon_0^3 + 2\epsilon_0\epsilon_2$
- Type 3. $V \propto \epsilon_0 + 4\epsilon_0^3 + 0.0032 \epsilon_3$

Comparing this with the behaviour of the equivalent system without the zeroing network (Section 6.2) it can be seen that the only change is the increase in the magnitude of the first order ϵ_3 interaction coefficient from 0.0003 to 0.0032 . When a zero offset equivalent to $\epsilon_0 = 0.001$ is introduced, the only change to the system behaviour is an increase in the ϵ_3 interaction coefficient from 0.0032 to 0.00324 . This change is not significant at the 0.01% accuracy level.

It is therefore evident that for a nulling system, at least for R_5 values of the order of $100 \text{ k}\Omega$, the zero offset may be changed over quite a wide range without changing the calibration equations.

For a nulling system there are two possible alternative arrangements of the zero offset resistor network. The first of these is the 90° rotated version mentioned previously with R_7 across the bridge output and R_6 connected to one of the power supplies. Calculations of the behaviour of this arrangement (with $R_5 = 100 \text{ k}\Omega$, $R_6 = 10 \text{ k}\Omega$ and $R_7 = 1 \text{ k}\Omega$) showed that an offset equivalent to $\epsilon_0 = 0.001$ produced a direct sensitivity change of 0.2% and complex type 2 and 3 interaction changes which each contributed output changes of about 0.2% for $\epsilon_0 = \epsilon_2 = \epsilon_3 = 0.002$. The second possible zero offset resistor network arrangement involve a 180° rotation around the bridge with R_6 connected to the corner of the bridge diagonally opposite the corner connected to the rebalancing resistor R_5 . This second arrangement behaves in a similar manner to the standard network except that a $\epsilon_0 = 0.001$ zero offset change introduces a $0.004 \epsilon_2$ term into the type 2 behaviour. Both of the alternative zero offset network connections are inferior to the standard arrangement and should not be used.

6.5 Implications for the use of semi-conductor strain gauges

The order of magnitude of the gauge resistance changes considered here were appropriate to metal resistance gauges on metal balance structures. All of the significant, electrically produced, apparent interactions between load components could be described to sufficient accuracy by the normal second order balance calibration equations. However a number of third and higher order interactions were noted and these would rapidly become significant as the gauge resistance changes became larger. For semi-conductor strain gauges with gauge factors typically more than an order of magnitude higher than metal gauges the usual second order description of a balance would be inadequate if significant strain arithmetic was used. This would obviously not be a problem if the strain levels were very low (as is the case for some low density wind tunnel balances) and the semi-conductor gauges were used simply to obtain a measurable output.

For high strain level use of semi-conductor gauges, care would have to be taken with the balance design to ensure good separation of the load components by mechanical means.

It appears probable that resistive zero offset networks such as those considered earlier would pose a number of problems at high gauge resistance change levels. It is suggested that it would be safer to use a relatively low gain buffer amplifier connected directly to the bridge without any zero offset network. Any necessary offset adjustments could be made with a summing amplifier following the buffer.

The most appropriate readout device for a high output semi-conductor gauge bridge would be a high input resistance amplifier. Low input resistance amplifiers and nulling systems would both have a significant cubic non-linearity in their output.

7. CONCLUSION

In multi-component strain gauge wind tunnel balances it is common practice to use four arm bridges of gauges arranged to produce an output from one load component and not from other load components which also cause significant strains under the gauges. This system, which is referred to as "strain arithmetic", relies on the fact that there is fundamentally one output-producing pattern of strains and three non-output-producing patterns. It is shown that interactions arise between the output-producing and non-output-producing strain patterns and that these interactions are dependent on the nature of the readout equipment used. Precautions which must be observed to obtain 0.01% accuracy levels are investigated.

Specific conclusions are:

1. Nulling and non-nulling readout systems cannot be substituted without a complete balance recalibration for each system. The use of a transfer standard to determine sensitivity ratios is not adequate.
2. Amplifiers of different input resistance cannot in general be interchanged without a complete recalibration.
3. The sensitivity of nulling readout systems can only be altered over a limited range without a recalibration being required.
4. Systems of the same type but employing different zero offset adjusting resistor networks cannot be interchanged.
5. Care must be taken when adjusting zero offset controls with non-nulling systems. Zero offset changes can alter the interactions between channels.
6. Strain arithmetic must be avoided when high output semi-conductor strain gauges are used if third and higher order interactions are to be kept to an acceptably low level.

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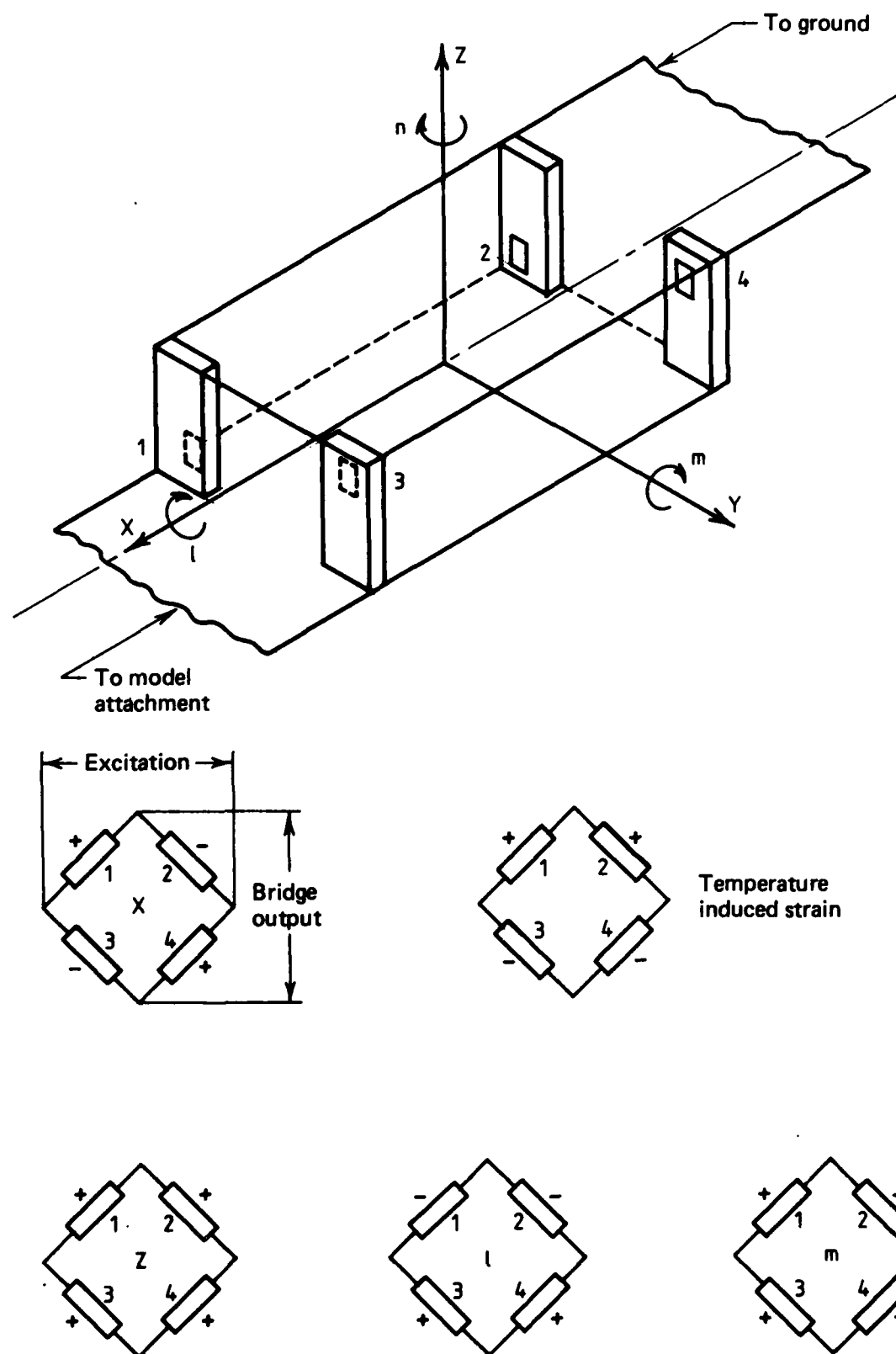
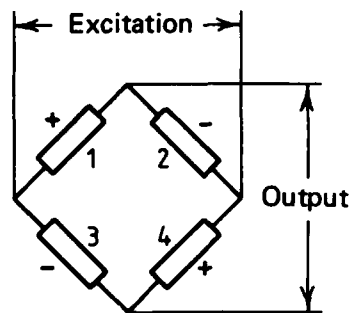
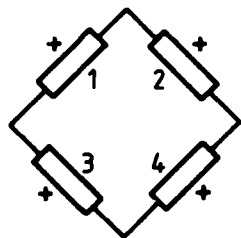


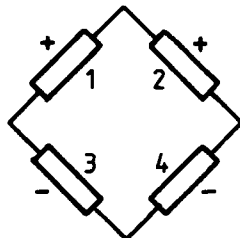
FIG. 1 FOUR BEAM AXIAL FORCE BALANCE — USE OF STRAIN ARITHMETIC.



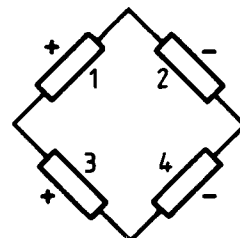
Primary output-producing strain pattern (Type 0)



Type 1

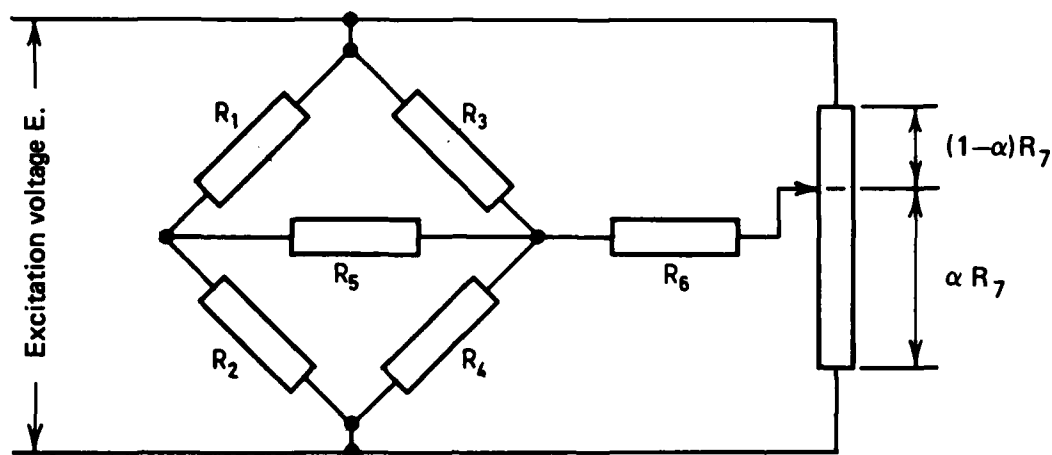


Type 2

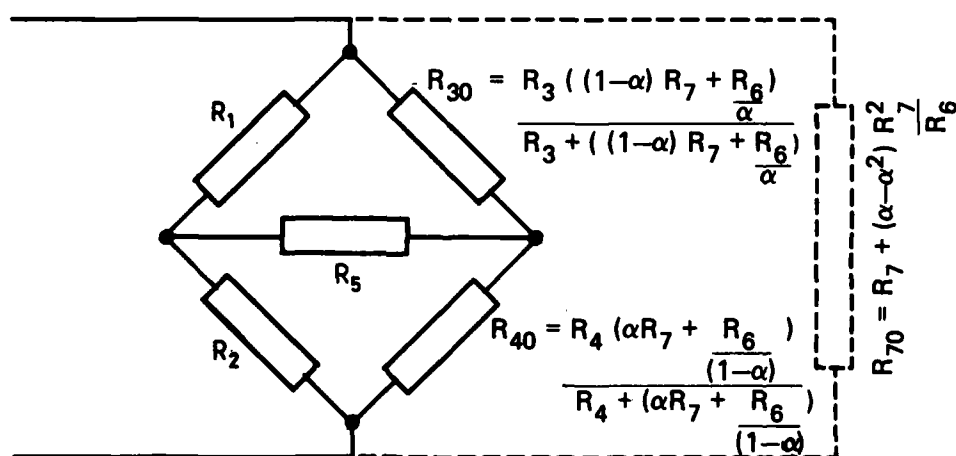


Type 3

Secondary non-output-producing strain patterns



Circuit for non-nulling system with offset
adjusting network



Simplified circuit

FIG. 3 NON-NULLING SYSTEM CIRCUIT DIAGRAM

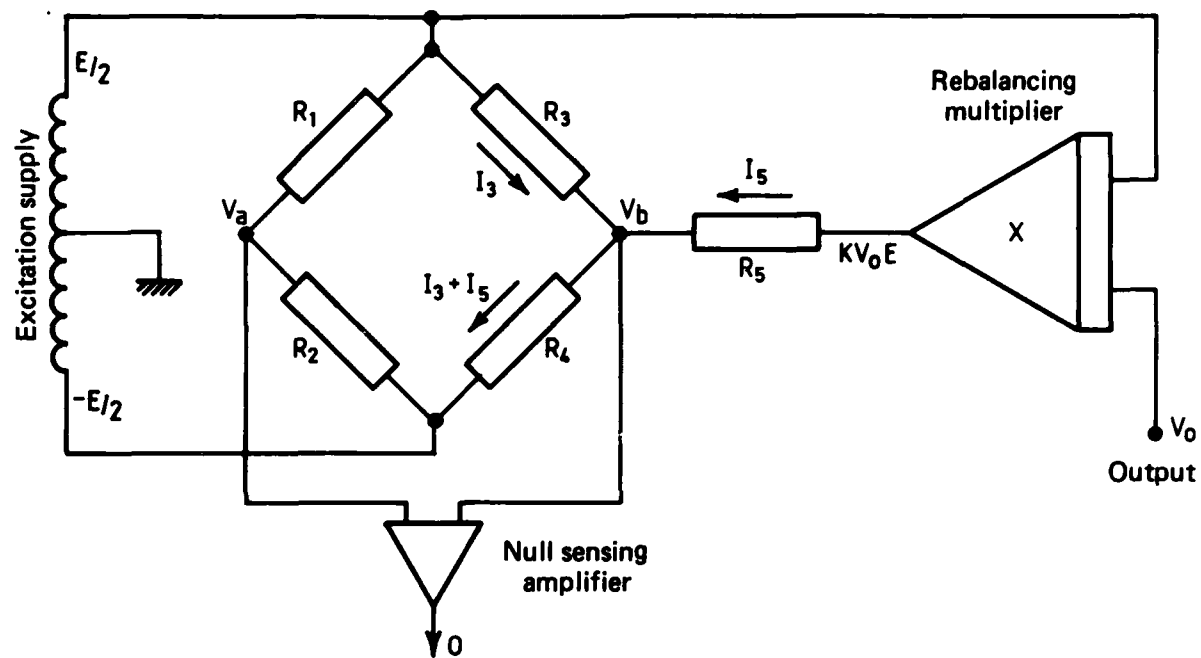


FIG. 4 NULLING SYSTEM CIRCUIT DIAGRAM.

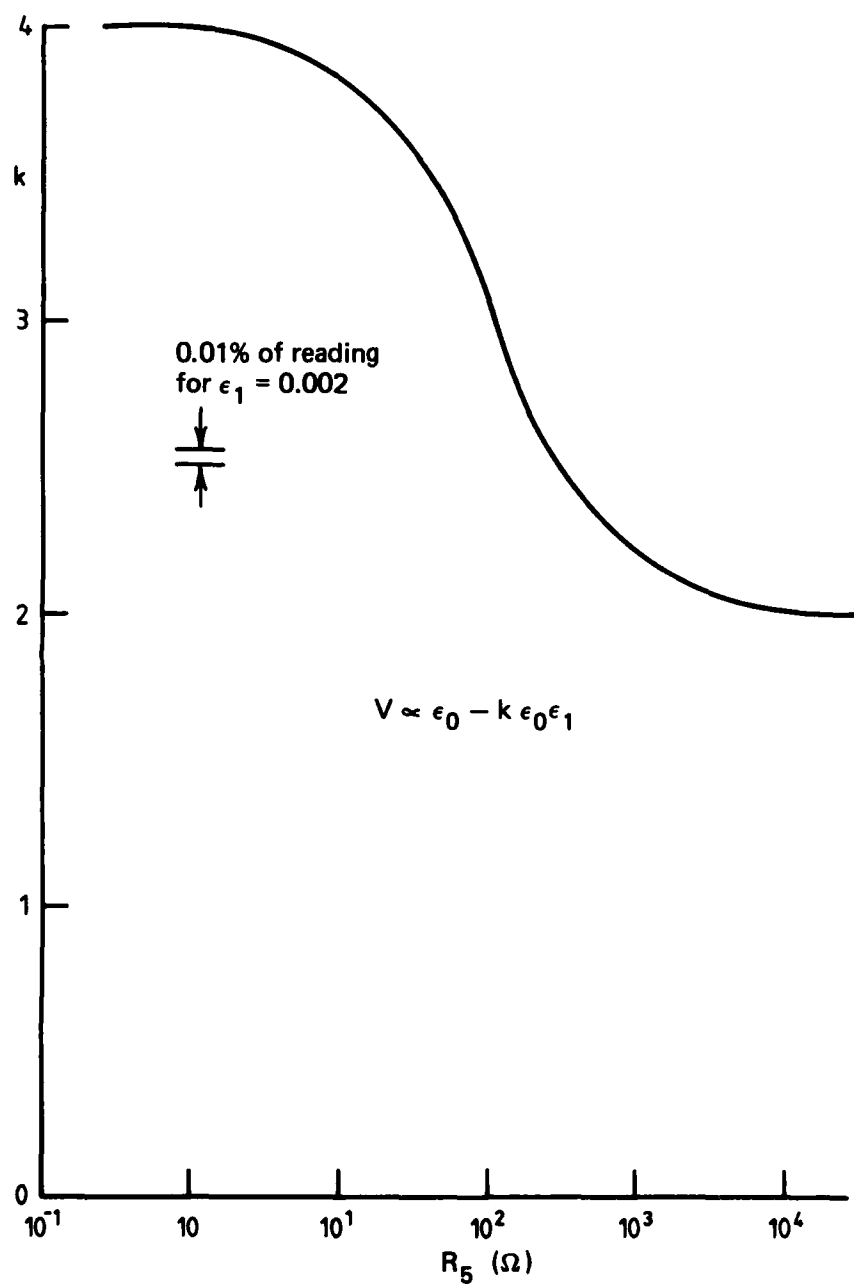


FIG. 5 VARIATION OF SECOND ORDER $\epsilon_0 \epsilon_1$ INTERACTION WITH AMPLIFIER INPUT RESISTANCE.

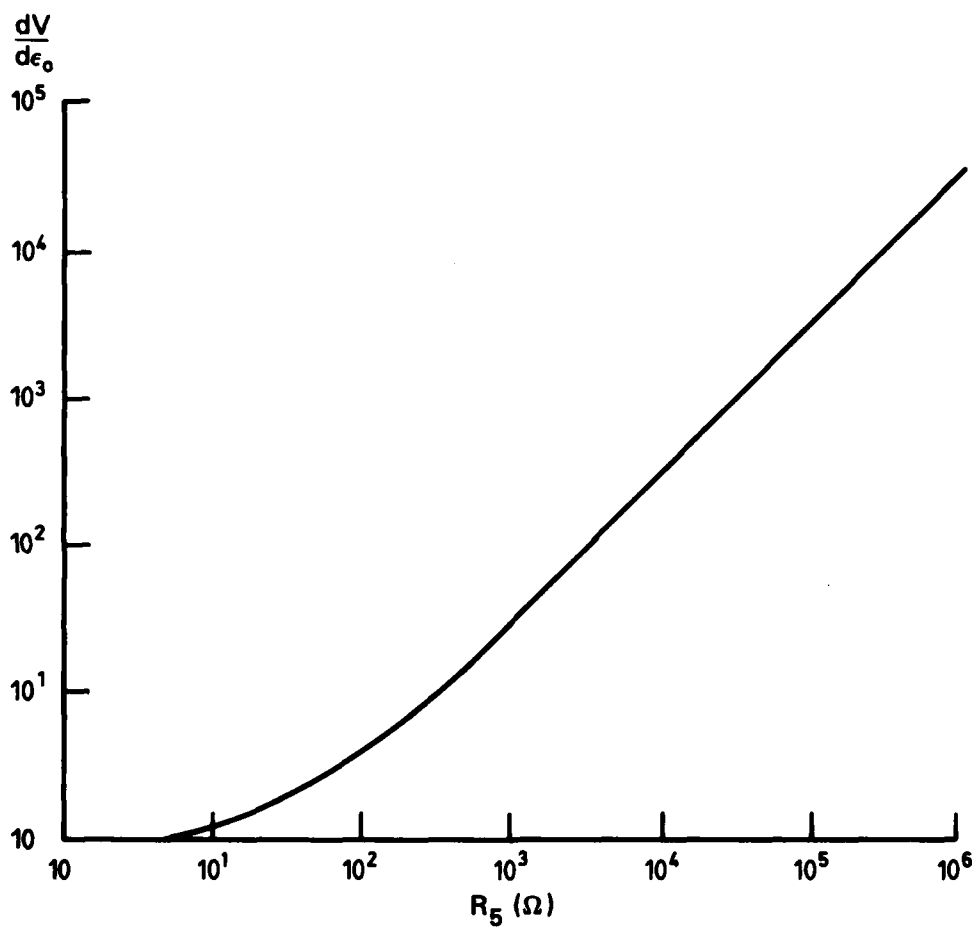


FIG. 6 VARIATION OF GAIN WITH REBALANCING RESISTOR VALUE FOR NULLING SYSTEM.

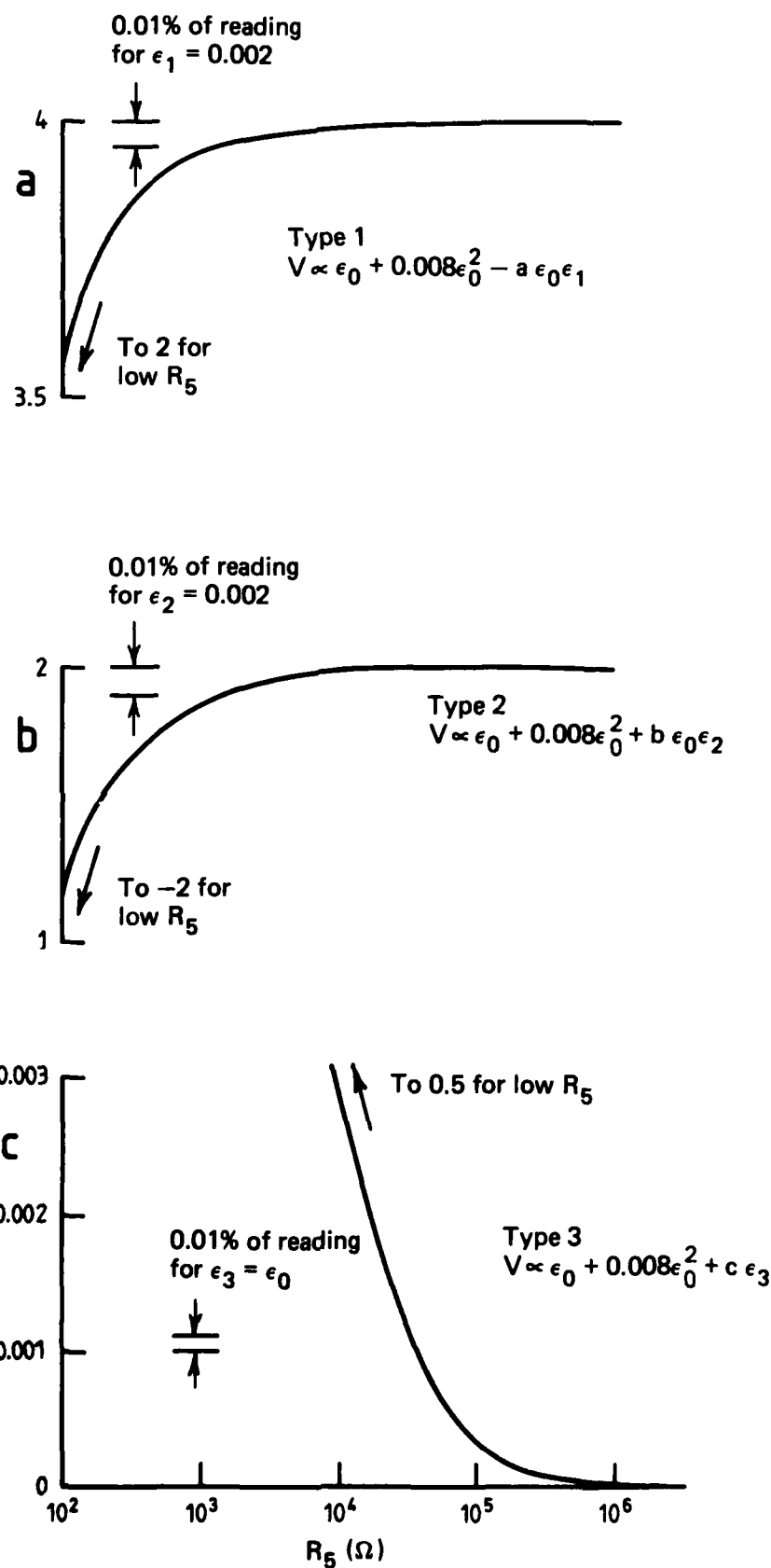


FIG. 7 VARIATION OF INTERACTIONS WITH REBALANCING RESISTANCE – NULLING SYSTEM

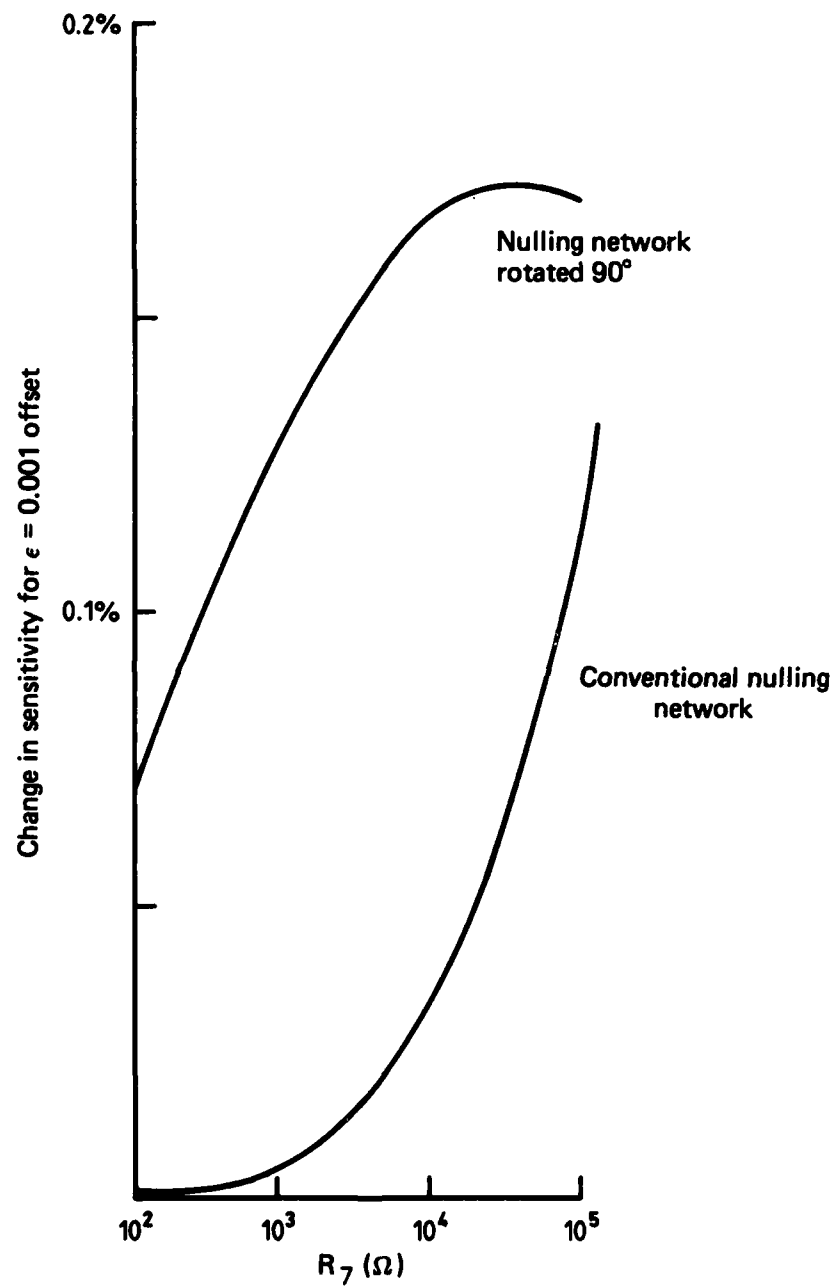


FIG. 8 CHANGE IN SENSITIVITY WITH ZERO OFFSET —
NON-NULLING SYSTEM $R_5 = 10^9 \Omega$

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